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Review Article

Climate Change and Fruit Crop Production: Emerging Challenges and Adaptation Strategies

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ABSTRACT

Climate change is increasingly affecting fruit crop production through rising temperatures, altered rainfall patterns, drought, heat waves, extreme weather events, and shifting pest and disease dynamics. These challenges can reduce flowering, fruit set, yield, quality, and post-harvest longevity, threatening the sustainability of fruit-based farming systems. Adaptation strategies such as climate-resilient cultivars, improved irrigation and water conservation, protected cultivation, integrated pest management, soil health improvement, canopy management, and precision agriculture can enhance crop resilience. Diversification of fruit species and cropping systems, climate-based forecasting, and efficient resource management further strengthen adaptation capacity. Integrating these approaches is essential for maintaining productivity, profitability, and food security under changing climatic conditions.

Keywords: *Climate change; Fruit crops; Chilling requirement; Phenology; Adaptation strategies.*

INTRODUCTION

Fruit crops occupy a distinctive position in global agriculture. They are nutritionally dense, economically remunerative, employment-intensive and, unlike annual field crops, they are perennial investments that must remain productive in the same location for two to four decades. This longevity is precisely what makes them vulnerable. An annual crop can be replaced with a different cultivar or even a different species in the following season, whereas an orchard planted today commits the grower to a fixed genotype, rootstock, planting density and site for a generation of changing weather. Consequently, even modest directional change in temperature or rainfall can convert a well-chosen site into a marginal one long before the orchard reaches the end of its economic life (Ramírez & Kallarackal, 2015).

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The physical evidence of change is unambiguous. Global surface temperature in 2011–2020 was 1.09 °C higher than in 1850–1900, with warming over land (1.59 °C) considerably greater than over the oceans, and each of the last four decades has been successively warmer than any preceding decade since 1850 (IPCC, 2021). Warming is accompanied by more frequent and more intense heat extremes, heavier precipitation events in many regions, and increasing agricultural and ecological drought in others (IPCC, 2021). For horticulture, these aggregate statistics matter less than their seasonal expression: a warmer winter, a hotter flowering week, an unseasonal spell of rain at harvest, or a single hailstorm can each be decisive for a fruit crop.

The exposure is large in scale. World fruit production reached about 910 million tonnes in 2021, a growth of 59 per cent since 2000, driven by both area expansion and intensification (FAO, 2022). India, the second largest producer of fruits globally, harvested about 107.1 million tonnes from 7.02 million hectares in 2021–22, with banana, mango and citrus contributing the bulk of the tonnage (Government of India, 2022; Figure 1). Because a substantial share of this output comes from rainfed or partially irrigated orchards managed by smallholders, the sensitivity of fruit systems to climate variability translates directly into rural income risk (Wheeler & von Braun, 2013).

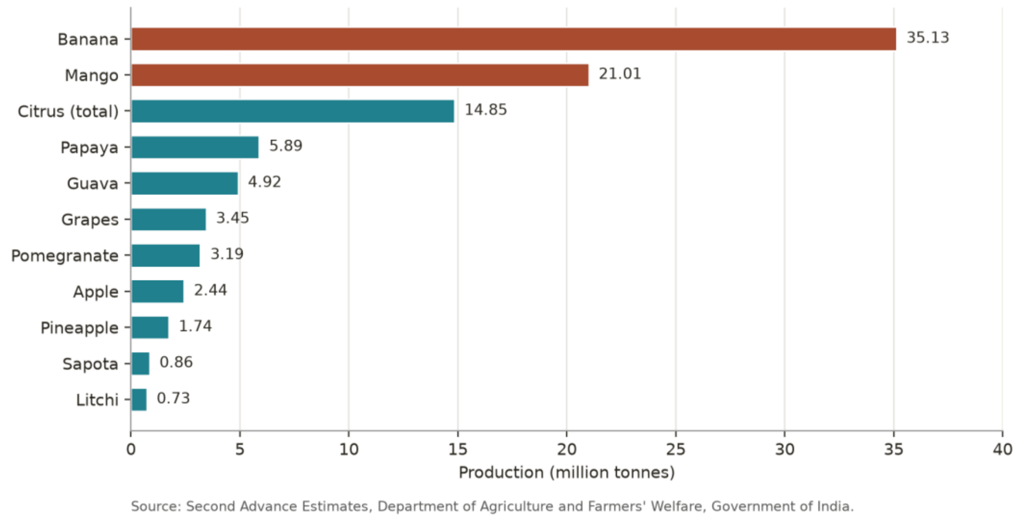

Figure 1. Production of major fruit crops in India, 2021–22
(Total fruit production: 107.1 million tonnes from 7.02 million ha)

Fruit crops also respond to climate in ways that are qualitatively different from cereals. Their yield is the outcome of a multi-year sequence: floral induction in one season, dormancy and chilling accumulation in winter, bud break and bloom, pollination and fruit set, cell division and expansion, ripening, and finally postharvest handling. A climatic perturbation at any one of these stages can be expressed as reduced yield or as reduced quality in the same or the following year, and quality is often the more economically damaging of the two because fruit is sold on appearance, size, colour, sweetness and shelf life (Moretti et al., 2010).

EMERGING CHALLENGES

Loss of Winter Chill and Erratic Dormancy Release

Temperate fruit species require a species- and cultivar-specific accumulation of cool winter hours to break endodormancy. Apple typically demands 1,200–1,500 hours below 7°C, and accumulation below roughly 1,000 hours results in delayed, staggered and incomplete bud break with poor yield and quality (Rai et al., 2015). Declining chill is now one of the best-documented climate signals in perennial horticulture. Global analyses project that safe winter chill availability will contract sharply in most growing regions, with the steepest relative losses in already-marginal warm-winter zones (Luedeling et al., 2011; & Luedeling, 2012). Reviews of fruit crops place the expected reduction in chilling hours at 30–60 per cent by 2050 and up to 80 per cent by 2100 (Bhattacharjee et al., 2022), a trajectory summarised in Figure 3a. Atkinson et al. (2013) further show that declining chill interacts with warmer forcing conditions, so that the timing of dormancy release becomes less predictable rather than simply earlier.

The Indian Himalaya provides a well-studied case. Rana et al. (2011) reported a 1.8–4.1 °C rise in apple-growing areas of Kullu and Shimla over two decades, an annual decline of 36.8 mm in snowfall across 21 stations between 2,000 and 4,000 m, and declining chill unit accumulation at all elevations up to 2,400 m, while chill units increased at 2,700 m at about 25 units per year. The commercial consequence has been a progressive upward migration of the apple belt: orchards established at 1,200–1,500 m in the 1980s gave way to plantings at 1,500–2,500 m in the 2000s, and by 2014 apple was being cultivated above 3,500 m in parts of the region (Basannagari & Kala, 2013). Figure 2 depicts this shift. Low-elevation districts have lost area outright; Rai et al. (2015) record a decline of as much as 77 per cent in apple area at Solan between 1981 and 2007.

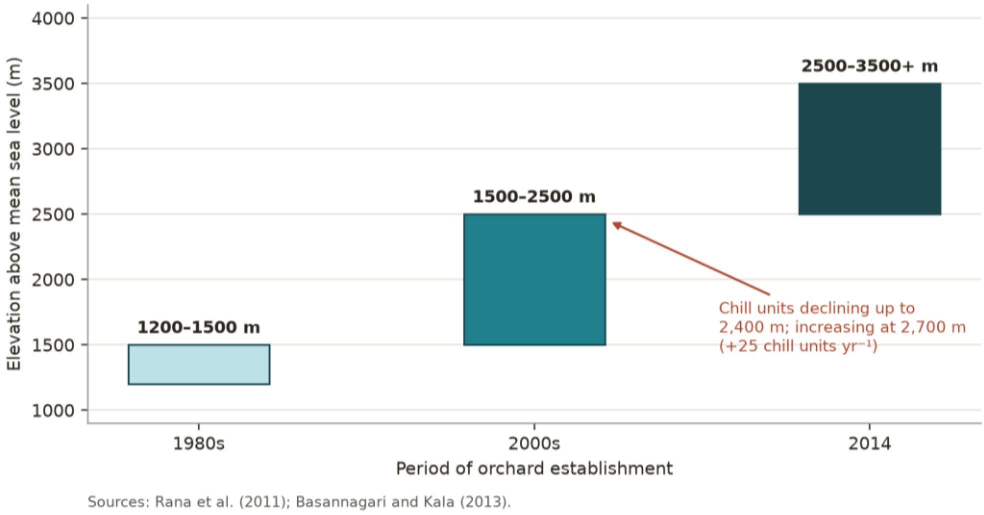

Figure 2. Upward shift of the economically suitable apple belt in the Indian Himalaya (Himachal Pradesh)

Advancement and Disruption of Phenology

Warming advances the phenological calendar of most fruit species. Long-term European records show earlier bud break, flowering and harvest in pome and stone fruits over recent decades, with advances of several days per decade attributable to rising late-winter and spring temperatures (Chmielewski et al., 2004; & Legave et al., 2013). In grapevine, earlier budburst, flowering, veraison and maturity compress the ripening period into hotter parts of the season, raising sugar and lowering acidity and altering aroma composition, with direct consequences for wine style and regional suitability (Jones et al., 2005; & van Leeuwen & Darriet, 2016).

Tropical and subtropical species show more complex behaviour because their flowering depends on the interaction of temperature, moisture stress and shoot maturity rather than on chilling alone. In mango, warm spells during floral induction promote vegetative flushing at the expense of panicle emergence, while rainfall or high humidity at anthesis reduces pollination efficiency and increases the incidence of malformation and anthracnose; erratic winter temperatures have produced irregular, extended and multiple flowering waves in Indian conditions (Rajan, 2012; & Normand et al., 2015). Litchi and other subtropical fruits similarly depend on a cool, dry pre-flowering phase, and warm winters coupled with heat and moisture stress during fruit development cause flower and fruit abscission, cracking and reduced pulp development (Bhattacharjee et al., 2022). Two further risks follow from earlier bloom: exposure of open flowers to late radiation frost, and desynchronisation between flowering and the activity peaks of pollinators, which reduces fruit set independently of the tree's own physiology (Ramírez & Kallarackal, 2015).

Heat Stress, Sunburn and Water Deficit

High temperature during fruit growth acts through several mechanisms. Photosynthesis declines above species-specific optima while respiration continues to rise, reducing net assimilate supply; pollen viability and stigma receptivity fall sharply within a narrow thermal band; and elevated night temperature increases respiratory carbon loss, reducing fruit size and soluble solids (Hatfield & Prueger, 2015; & Rao et al., 2016). Where high irradiance accompanies high air temperature, fruit surface temperature can exceed air temperature by 10–18°C, producing sunburn. In apple, sunburn browning occurs at fruit surface temperatures of about 46–49 °C, with photo-oxidative damage in the intermediate range, while sunburn necrosis appears above 52°C (Schrader et al., 2003; & Racskó & Schrader, 2012). These thresholds are summarised in Figure 3b. Sunburn commonly causes crop losses exceeding 10 per cent in semi-arid production zones and can reach far higher levels in extreme seasons (Racskó & Schrader, 2012).

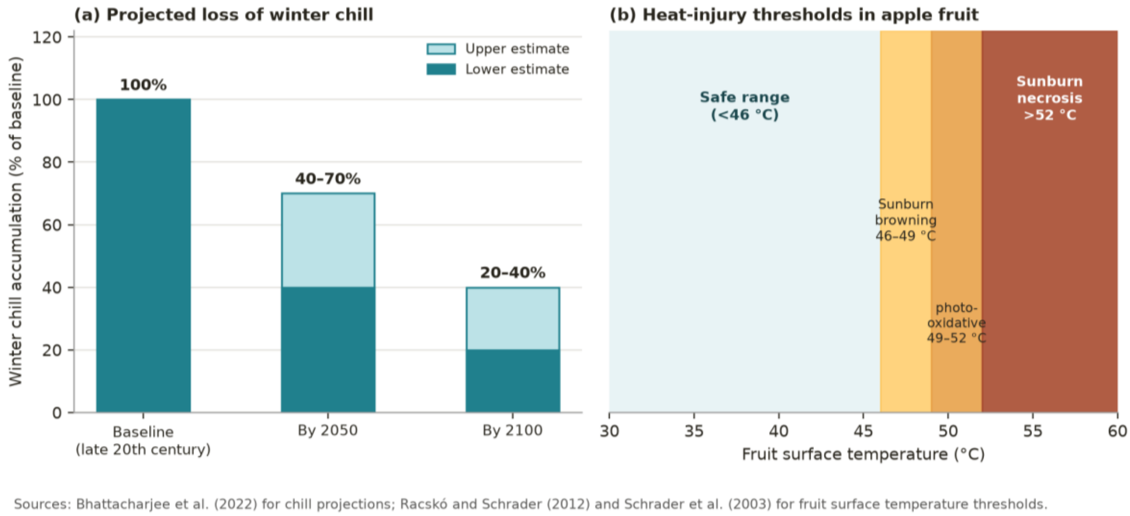

Figure 3. Two temperature-driven bottlenecks in fruit production: declining winter chill and rising heat injury

Water is the other limiting axis. Warmer air increases evaporative demand at the same time as rainfall becomes more concentrated in intense events separated by longer dry spells, so orchards experience both waterlogging and drought within a single season (IPCC, 2022). Deficit during cell division reduces final fruit size irreversibly, while fluctuating soil moisture near maturity causes fruit cracking and splitting in litchi, pomegranate, citrus and grape. In coastal and canal-irrigated regions, declining water tables and rising secondary salinity compound the stress, and salinity–heat–drought combinations are physiologically distinct from any single stress applied alone (Mittler, 2006).

Elevated Carbon Dioxide and Fruit Quality

Rising atmospheric carbon dioxide, which had exceeded 415 ppm by 2020 (Bhattacharjee et al., 2022), is the one component of climate change that can be directly beneficial. Enrichment typically increases photosynthetic rate, water-use efficiency, biomass and, in several fruit species, sugar accumulation (Ramírez & Kallarackal, 2015). However, the benefit is neither universal nor unconditional.

It saturates at higher concentrations, depends on adequate nitrogen and water supply, and is frequently offset by the accompanying temperature rise. Sugiura et al. (2013) used four decades of Japanese apple orchard records to show that warming had already reduced fruit firmness and acid concentration and altered watercore and taste attributes, demonstrating that composition changes are measurable in commercial orchards rather than only in controlled chambers. Elevated carbon dioxide combined with heat also tends to dilute mineral and, in some cases, antioxidant concentrations relative to carbohydrate, so a larger fruit is not necessarily a better fruit (Bisbis et al., 2018). Because much of the value of fruit resides in colour, aroma, texture and nutritional density, quality effects deserve equal weight with yield effects in climate impact assessment (Moretti et al., 2010).

Pests, Diseases and Pollinators

Warming alters the biotic environment of orchards as strongly as the abiotic one. Higher temperatures shorten insect generation times and raise metabolic rates, increasing the number of generations completed per season and the amount of tissue consumed per insect; global analysis indicates that crop losses to insect pests rise substantially per degree of warming (Deutsch et al., 2018). Milder winters improve overwintering survival, advancing and enlarging spring populations. Simultaneously, pests and pathogens are shifting poleward and upslope at rates of the order of kilometres per year, exposing previously safe production zones such as high-elevation apple belts to fruit flies, borers, mites and scab or powdery mildew epidemics (Bebber et al., 2013). Changed rainfall distribution modifies disease risk in both directions: unseasonal rain and prolonged leaf wetness favour anthracnose, scab and bacterial diseases, whereas drier spells favour mites and thrips. Pollination is a further point of vulnerability, since bee foraging activity is temperature-dependent and both drought and heat reduce nectar quality, so the pollination service can fail even where flowers are abundant (Ramírez & Kallarackal, 2015).

Extreme Events and Postharvest Losses

For perennial fruit, single extreme events can be more damaging than gradual trends. Hailstorms destroy the marketable surface of maturing fruit, cyclonic winds uproot banana and papaya plantations, late frosts kill open flowers, and heat waves coinciding with bloom or harvest cause simultaneous loss of quantity and quality (IPCC, 2022; & Malhotra, 2017). Losses extend beyond the orchard gate. Higher field temperature at harvest raises fruit pulp temperature and respiration rate, accelerating ripening and softening, increasing water loss and shortening shelf life, while warmer ambient conditions increase the energy demand and cost of precooling and cold storage (Moretti et al., 2010). Where cold chains are weak, this compresses the marketing window and forces distress sales, so climate-induced postharvest loss becomes an economic amplifier of the biological impact. Because most extreme events strike within a few days, and often within a few hours, their damage cannot be managed by seasonal planning alone; it requires standing physical protection such as netting, and financial protection such as insurance, both of which must be in place before the event occurs. Recovery from structural damage in a perennial system is also slow, since a destroyed orchard needs several years to return to full bearing, so a single severe season can depress income over multiple subsequent years.

ADAPTATION STRATEGIES

Adaptation in fruit crops must operate on three time horizons simultaneously: immediate tactical protection of the current crop, medium-term modification of orchard management, and long-term genetic and locational change. Figure 4 organises the drivers, responses and options discussed below into a single framework.

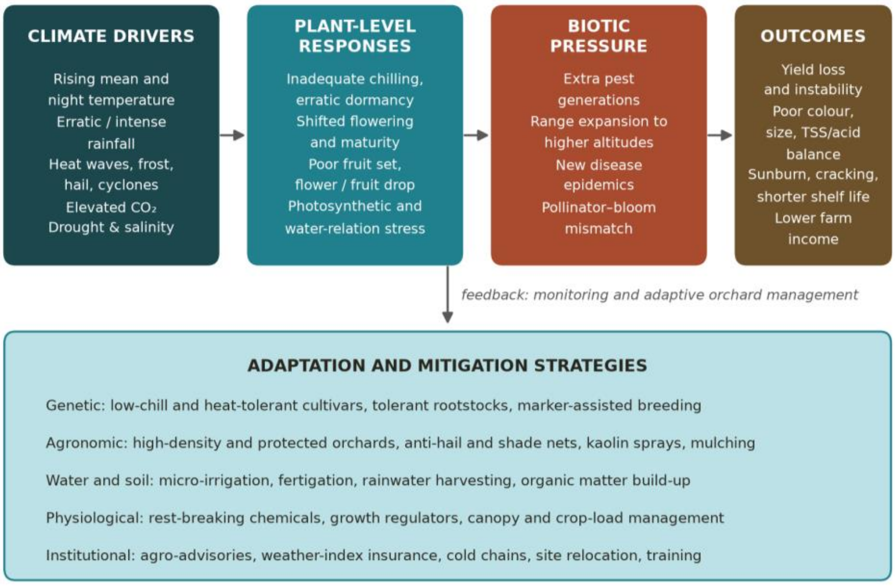

Figure 4. Conceptual framework linking climate drivers to fruit crop responses and adaptation options

Genetic and Varietal Adaptation

Cultivar choice is the most durable adaptation lever. For temperate species, low-chill cultivars and cultivars with wider adaptability allow production to continue where chill has declined, and such material already exists in apple, peach, plum, pear and grape breeding programmes (Luedeling, 2012; & Rai et al., 2015). For tropical and subtropical species, selection targets heat tolerance during flowering, tolerance to erratic flowering, resistance to cracking and physiological disorders, and tolerance of drought and salinity. Rootstocks provide a complementary route, conferring drought, waterlogging, salinity and soil-temperature tolerance without altering scion quality. Crop wild relatives and landraces conserved in gene banks are the primary reservoir of these traits, and marker-assisted selection and genomic tools can shorten the long breeding cycles that otherwise make perennial improvement slower than the rate of climate change (Ramírez & Kallarackal, 2015; & Malhotra, 2017). Diversification of the cultivar portfolio within a holding, and of species across a region, spreads phenological risk so that a single adverse spell does not affect the entire crop.

Orchard Design and Canopy Management

Modern orchard architecture can buffer climate stress. High-density and meadow systems with dwarfing rootstocks reach bearing earlier, allow faster cultivar turnover in response to changing conditions, and permit precise canopy control. Training systems that keep fruit shaded within the canopy reduce sunburn, and judicious summer pruning avoids exposing fruit that developed under shade. Reflective particle films based on kaolin, calcium carbonate or similar materials lower fruit surface temperature by several degrees and are among the most cost-effective interventions against sunburn (Racskó & Schrader, 2012). Overhead shade nets of 15–30 per cent shading, anti-hail netting, windbreaks and evaporative cooling by overhead microsprinklers give direct physical protection against radiation, hail and heat, and protected cultivation is increasingly viable for high-value crops such as strawberry, papaya and table grape (Malhotra, 2017). Crop-load management through thinning matches fruit number to the assimilate supply actually available in a stressed season, protecting size and soluble solids.

Water and Soil Management

Because water scarcity and rainfall variability are the dominant risks in most fruit belts, efficient water management is central. Drip and micro-sprinkler irrigation coupled with soil-moisture or evapotranspiration-based scheduling, fertigation, and regulated deficit irrigation at phenologically safe stages conserve water while maintaining quality.

Rainwater harvesting, farm ponds, in-situ moisture conservation through basins and trenches, and organic and plastic mulching extend the effective growing period in rainfed orchards. Soil organic matter build-up through cover crops, green manuring, composting and biochar improves water-holding capacity, buffers soil temperature, sustains microbial activity and simultaneously contributes to carbon sequestration, making orchards part of the mitigation response as well as its beneficiary (Malhotra, 2017; & IPCC, 2022). Integrated nutrient management with potassium, calcium, boron and zinc supplementation improves tolerance to heat and water stress and reduces disorders such as cracking and bitter pit.

Physiological and Chemical Interventions

Where chill accumulation is insufficient, rest-breaking agents and plant bioregulators can partly substitute for cold. Hydrogen cyanamide, mineral oils, potassium nitrate and thiourea are used to promote uniform bud break in grape, peach and apple, though their efficacy is site- and dose-specific and they carry environmental and residue considerations. Paclobutrazol and ethephon are used in mango to regulate flowering, while gibberellic acid, naphthalene acetic acid and calcium sprays are used to manage fruit set, retention and cracking. Osmoprotectants, antitranspirants, salicylic acid, brassinosteroids and biostimulants have shown promise in reducing oxidative injury under heat and drought (Rao et al., 2016). These measures are tactical and should complement, not replace, genetic and structural adaptation.

Digital Tools, Institutions and Policy

Adaptation depends as much on information and institutions as on technology. Automatic weather stations, in-orchard temperature and fruit-surface-temperature sensors, phenology and chill-unit models, disease and pest forecasting systems, and remote sensing based orchard monitoring convert weather data into actionable advisories on irrigation, spraying, thinning and harvest timing. Weather-index insurance products transfer residual risk, provided that indices are calibrated to horticultural rather than cereal phenology. Investment in precooling, controlled-atmosphere storage, refrigerated transport and processing capacity reduces climate-induced postharvest loss and widens marketing options. Region-level land-use planning based on updated agro-climatic zonation can guide the relocation of production to newly suitable areas, while extension, farmer field schools and grower associations are needed to move all of these options from research stations into commercial orchards (Malhotra, 2017; & Wheeler & von Braun, 2013).

RESEARCH GAPS AND FUTURE OUTLOOK

Several gaps limit confident adaptation planning. First, most experimental evidence isolates single stresses, whereas orchards experience heat, drought, high irradiance and elevated carbon dioxide simultaneously, and the combined response is not additive (Mittler, 2006). Second, chill models were largely developed and validated for temperate conditions and perform inconsistently in warm-winter subtropics, weakening projections precisely where the risk is highest (Luedeling, 2012). Third, long-term phenological and yield datasets for tropical fruits are sparse compared with those for grape and pome fruit, limiting attribution and model calibration. Fourth, quality and nutritional responses are under-quantified relative to yield, despite their greater economic weight. Fifth, the economics of adaptation, including the cost, adoption rate and returns of netting, cooling and cultivar replacement on smallholdings, remains poorly documented. Coordinated long-term orchard networks, open phenological databases, multi-stress field experiments and participatory on-farm trials are needed to close these gaps.

CONCLUSION

Climate change is not a distant scenario for fruit crops but an operating condition already recorded in orchard data. Warming winters are eroding chill accumulation and displacing temperate fruit belts to higher elevations; earlier and erratic flowering is increasing exposure to frost, heat and pollination failure; higher temperature and irradiance are causing sunburn, small fruit and compositional change; variable rainfall is producing drought, waterlogging and cracking in the same season; and pest and pathogen pressure is intensifying and expanding into formerly safe zones. Elevated carbon dioxide offers a partial and conditional offset that rarely compensates for the accompanying thermal and hydrological stress, and quality deterioration may prove more costly than yield loss because fruit is priced on appearance and taste. Because orchards are long-lived and site-bound, adaptation decisions made now determine performance for decades, which makes anticipatory action both more difficult and more valuable than in annual crops. The response must be layered: resilient germplasm and rootstocks as the foundation, climate-proofed orchard design, canopy and water management as the working layer, physiological and chemical interventions as tactical tools, and advisory services, insurance, cold chains and agro-climatic planning as the enabling environment. Fruit production also has mitigation value, since well-managed perennial orchards sequester carbon in wood and soil. Aligning breeding programmes, extension systems and public investment with this layered strategy is the practical route to sustaining productivity, quality and grower incomes in a warming climate.

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